EFFECT OF HEAT TREATMENT ON FATIGUE LIFE

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ABSTRACT

The main purpose of this project is to determine the effect of various heat treatment processes on fatigue life of mild steel specimen. The study of fatigue life and effect of heat treatment is very important in order to increase the hardness of the material and its life before failure. The influence of heat treatment process to the specimen has been investigated. Total eighteen specimens have been machined where six were oil quenched, six were tempered and another six remained as received. The rotational bending fatigue test was conducted on all prepared specimens at room temperature with stress ratio of -1. From the fatigue test, the results show that tempered specimens has highest fatigue life compared to other two conditions. After the fatigue test have been done, the fracture surface of failed specimens were analysed to ensure that the specimens were failed due to fatigue. Based on the analysis, the mild steel specimens failed due to fatigue with transgranular manners. It was observed that there are three distinct region on specimen’s fracture surface which are crack initiation, crack propagation and rapid fracture region.

ABSTRAK

Tujuan utama projek ini adalah untuk menentukan kesan pelbagai proses rawatan haba ke atas hayat lesu specimen rendah karbon. Kajian ke atas hayat lesu dan kesan rawatan haba amat penting untuk menambah kekerasan bahan dan hayatnya sebelum ia lesu. Pengaruh rawatan haba yang telah dilakukan ke atas bahan telah disiasat. Lapan belas bahan telah di mesin di mana enam telah dilindapkejutkan di dalam minyak, enam telah di tempa di udara persekitaran dan enam tidak dikenakan apa-apa rawatan haba. Ujian hayat lesu terhadap putaran telah dijalankan ke atas semua bahan pada suhu bilik dengan nisbah tekanan bernilai -1. Daripada ujian hayat lesu, keputusan menunjukkan bahawa bahan yang ditempa mempunyai jangka hayat lesu yang tinggi berbanding bahan di dalam keadaan lain. Selepas ujian hayat lesu telah dijalankan ke atas setiap bahan, permukaan bahan yang telah patah telah di analisis untuk menentukan bahawa bahan itu telah patah disebabkan oleh hayat lesu. Berdasarkan analisis, bahan rendah karbon yang telah diuji telah gagal mengikut cara ‘transgranular’. Ia telah diperhatikan bahawa permukaan itu terbahagi kepada tiga bahagian iaitu permulaan keretakan, perambatan keretakan dan kawasan kepesatan kepatahan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

N	Spindle speed
CS	Cutting Speed
d	Diameter of raw material
f	Feed
v_f	Feed rate
d_0	Initial diameter
d_f	Final diameter
T	Temperature
t	Time
R	Stress ratio
l	Length
S_{ut}	Minimum tensile strength
S_{yield}	Yield strength
S_e'	Endurance limit
K_f	Fatigue stress-concentration factor
q	Notch sensitivity
K_t	Stress-concentration factor
r	Notch radius
M	Moment
y	Radius of back part of specimen
I	Inertia
σ	Stress

N	Number of cycles to failure
F	Load

LIST OF ABBREVIATIONS

S-N	Stress-Cycles
BCC	Body Centered Crystal
FCC	Face Centered Cubic
AISI	American Iron and Steel Institute
VHN	Vickers Hardness Number

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Fatigue is a progressive and localized structural damage when the material is subjected to cyclic loading whereas the fatigue life is the number of cycles that will cause failure at a certain stress level. In this project, the effect of heat treatment on the fatigue life of low carbon steel will be investigated. For this purpose, the specimens with various heat treatments will be prepared and tested in tension-compression rotational bending fatigue test. The rotational bending fatigue experiment was carried out at room temperature, applying a fully reversed cyclic load with constant frequency and mean stress using a cantilever rotating-bending fatigue machine. Morphological study was carried out to observe the microstructure of the heat treated specimen. Fracture surface of specimens will be analysed using optical microscope.

1.2 OBJECTIVES

For this project, several objectives have been developed to be achieved:

1) To study the effect of various heat treatment on fatigue life of carbon steel.
2) To investigate the microstructure of carbon steel after being heat treated by various type of heat treatment.

1.3 PROBLEM STATEMENT

Fatigue is an engineering problem where it happens when a material is subjected to cyclic load. Low carbon steel is steel that has low carbon composition which is less than 0.25%. It is inherently easier to cold-form due to their soft and ductile nature. It is cheap and easy to get thus it is widely used in engineering structure. For example, in making pipes, chains, wire nail and some other machine part. But, it is often failed due to fatigue. So, in order to reduce the fatigue failure of low carbon steel, heat treating method such as quenching and tempering was used. Heat treatment is another way to reinforce steel and is the best way to increase the strength of the material. Thus, the fatigue failure problem will be decreasing.

1.4 SCOPE OF PROJECT

This project concentrated on how the various heat treatment methods affect the carbon steel fatigue life and its microstructure. The scope of this project includes the preparation of material where the carbon steel was taken from laboratory and then machined to desired dimension. After preparation of 18 specimens, the heat treatment processes take over. Two heat treatment processes were conducted, which are quenching and tempering. After heat treatment processes have been done, the microstructure and hardness of the specimen were investigated. Then, the specimens were subjected rotational bending fatigue test. Surface fracture of the failed specimen was analysed to make sure the specimen failed due to fatigue.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter discusses the literatures that are related to fatigue life on material such as low carbon steel. This chapter will review on the material that are used, the S-N curve, the processes that are used for specimens preparation, the heat treatment processes and the fatigue test on the specimen.

2.2 THE METALLURGY OF STEEL

When a small amount of carbon is added to iron, thus steel is obtained. So, all steel have some carbon and iron in its mechanical properties and a little bit of alloying elements since the influence of carbon on mechanical properties of iron is much larger than other alloying elements. It also can be said that steel is a crystalline alloy of iron, carbon and several other elements. These alloys vary both in the way they are made and in the amount of the materials added to the iron.

2.2.1 Plain Carbon Steel

Carbon steel is one of the most used steel. The properties of carbon steel depend on the amount of carbon that contains in the steel. Most of the carbon steel has a carbon content of less than 1%. Carbon steel is also used in many products that are commonly used such as structural beams, car bodies, kitchen appliances, and cans. There are three types of carbon steel that are low carbon steel, medium carbon steel and high carbon steel and each one of them differs in the amount of carbon that it contains. So, plain carbon steel is a type of steel that contains the maximum carbon content of 1.5% along with small percentages of silica, sulphur, phosphorus and manganese.

Low carbon steel or mild steel is a carbon steel that contains carbon up to 0.25% and responds to heat treatment as improvement in the ductility of the steel is concerned but has no effect on its strength properties.

Medium carbon steel is a carbon steel that contains carbon ranging from 0.25% to 0.7% and it improves in the machinability by heat treatment. This steel is especially adaptable for machining or forging where surface hardness is desirable

High carbon steel is plain carbon steel that contains carbon ranging from 0.7% to 1.05% and it is especially classed as high carbon steel. It is very hard in heat treatment and it will withstand high shear and wear and will be subjected to little deformation. There are also other properties of plain carbon steel that needs to be considered as shown in Table 2.1.

Table 2.1: Properties of low carbon steel

Material	**Density ($\times 10^3 kgm^{-3}$)**	**Thermal conductivity ($Jm^{-1}K^{-1}s^{-1}$)**	**Thermal expansion ($\times 10^{-6}K^{-1}$)**	**Young's modulus (GNm^{-2})**	**Tensile strength (MNm^{-2})**	**% elongation**
0.2% C Steel	7.86	50	11.7	210	350	30
0.4% C Steel	7.85	48	11.3	210	600	20
0.8% C Steel	7.84	46	10.8	210	800	8

Source: Raghavan (2001)

The atomic diameter of carbon is less than the interstices between iron atoms and so the carbon goes into solid solution of iron. As carbon dissolves in the gabs between the atoms, it distorts the original crystal lattice of iron. This change of crystal lattice of interferes with the external applied strain to the crystal lattice by mechanically blocking the dislocation of crystal lattices and the steel is now having higher mechanical strength. The more carbon added to the solid solution of iron, the more distortion it will made to the crystal lattice and thus the mechanical strength is increasing. Thus the high carbon steel has more carbon in the mechanical properties and low carbon steel has small amount of carbon in its mechanical properties. But by adding the carbon into iron, there are other properties that are influenced by the carbon that is the ductility which is the ability of iron to undergo plastic deformation. Thus, the more carbon added to the iron, the strength is increasing but the ductility is reduced. Adding carbon is not the only way to increase the strength of steel. More carbon amount means that when in welding process, it will cause trouble because of the strength. Figure 2.1 shows diagram of temperature versus weight % of carbon of carbon steel.

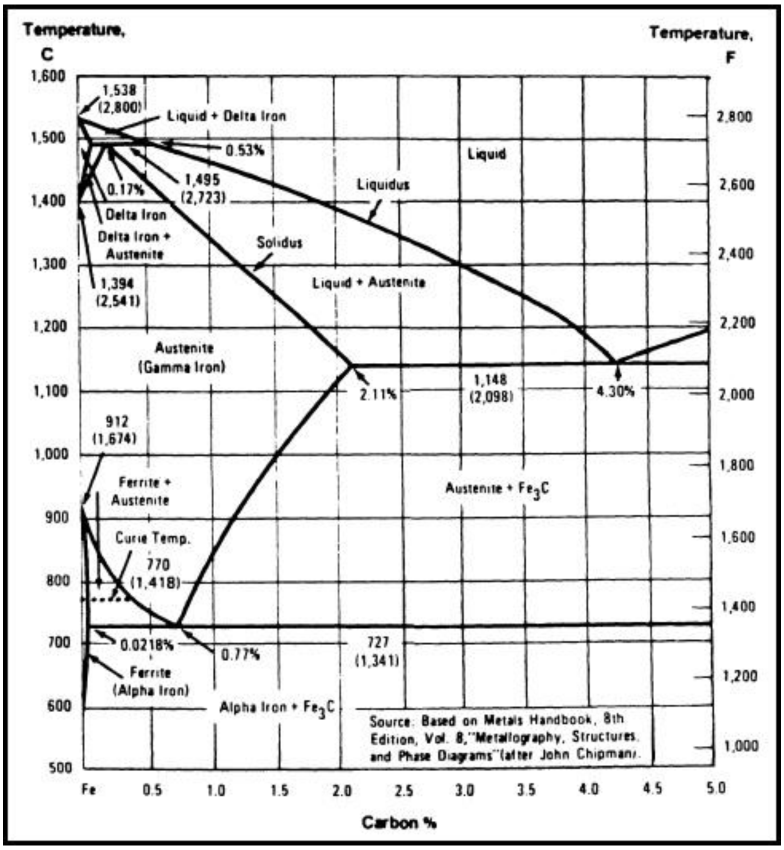

Figure 2.1: Temperature versus weight % of carbon of carbon steel

Source: Meier (2004)

Ferrite (α) is virtually pure iron with body centered cubic crystal structure (BCC). It is stable at all temperatures up to 9100°C. The carbon solubility in ferrite depends on the temperature where the maximum carbon amount is 0.02% at 723°C. Cementite is an Iron Carbide (Fe_3C), a compound iron containing 6.67% of carbon by weight. It is commonly used as a tool in lathe machine for machining the material. Pearlite is a fine mixture of ferrite and cementite arranged in lamellar form. It is stable at all temperatures below 723°C. Austenite (γ) is a face centered cubic structure (FCC). It is stable at temperatures above 723°C depending on the carbon content. It can dissolve up to 2% of carbon.

The maximum solubility of carbon in the form of Fe_3C in iron is 6.67%. If the addition is above the limit, it will result in formation of free carbon or graphite in iron. At 6.67% of carbon, iron transforms completely into cementite of Fe_3C that is Iron Carbide. Generally, carbon content in structural steels is in the range of 0.12-0.25%. Up to 2% of carbon, we will get a structure of ferrite + pearlite or pearlite + cementite depending on the whether the carbon content is less than 0.8% or beyond 0.8%. Beyond 2% carbon in iron a brittle cast iron is formed.

Furthermore, the hardness, brittleness and ductility are very important properties as they determine mainly the way these different carbon content steels are used. Considering the microstructure of slowly cooled steel for example mild steel with 0.2% carbon. Such steel consists of about 75% of proeutectoid ferrite that forms above the eutectoid temperature and about 25% of pearlite with pearlite and ferrite being microstructure components of steel. When the carbon content in steel is increased, the amount of pearlite increases until we get the fully pearlitic structure of a composition of 0.8% carbon. Beyond 0.8%, high carbon steel contain proeutectoid cementite n addition to pearlite.

But in slowly cooled carbon steels, the overall hardness and ductility of the steel are determined by the relative proportions of soft, ductile ferrite and the hard, brittle cementite. The cementite content increases with increasing carbon content, resulting in an increase of hardness and the decrease of ductility, as we go from low to high carbon steels.

There are also some limitations if carbon steels that are it there can't be strengthening beyond 100000 psi without significant loss in toughness (impact resistance) and ductility. Then, the large sections cannot be made with martensite structure throughout, and thus are not deep hardenable. Rapid quench rates are necessary for full hardening in medium-carbon leads to shape distortion and cracking of heat treated steels.

The characteristic of plain-carbon steels is that it has poor impact resistance at low temperatures. It also has a poor corrosion resistance for engineering problems. That means that it is easily corroded when the corroding element exists and it also oxidise readily at elevated temperature. Figure 2.2 shows three types of plain carbon steel microstructure.

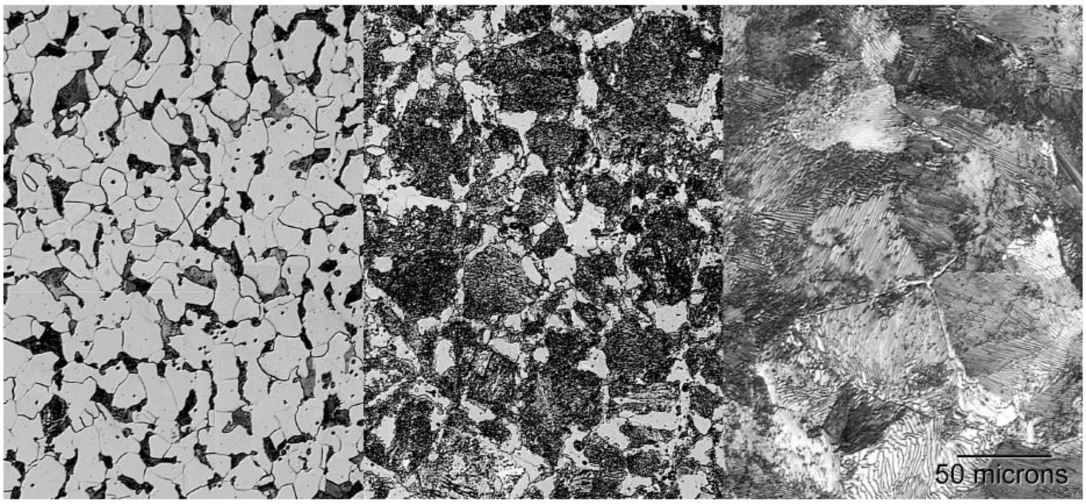

Figure 2.2: Three plain carbon steels, from left to right: 1018, 1045 and 1095. Increasing the carbon content (from 0.18% to 0.95%) causes the amount of ferrite (light) to decrease and the amount of pearlite (dark, lamellar) to increase.

Source: Meier (2004)

2.3 HEAT TREATMENT PROCESS

Heat treatment is a process of transformation of phases in the microstructures and properties of steel during heating and cooling to change the microstructure in a solid state. In heat treatment processes, the processing is most often entirely thermal and modifies only the structure of material. Thermomechanical treatments which modify components shape and structure and thermochemical treatments which modify surface chemistry and structure are also important processing approaches which fall into the domain of heat treatment.

Heat treatment is often associated with increasing the strength of material, but it can also be used to alter certain manufacturability objectives such as improve machining, improve formability, restore ductility after a cold working operation. Thus it is a very enabling manufacturing process that can not only help other manufacturing process, but can also improve product performance by increasing strength or other desirable characteristics. There are three main objectives that steels needed to be heat treated that are softening, hardening, and material modification.

2.3.1 Quenching

Quenching is a heat treatment process of rapid cooling of a workpiece to obtain certain material properties. This process is most commonly used to harden steel by introducing martensite, in which case the steel must be rapidly cooled through its eutectoid point, the temperature at which austenite becomes unstable. The common quenching medium: air, water and oil. Quenched material has relatively good proportion between yield strength and toughness due to fine dispersion of ferrite-cementite mixture. Yield strength of ferrite-cemetite mixture are higher if the grain size of previous austenite is finer. The grain size refinement of steel can be done by repeated alpha and gamma phase transformations. If the cyclic heat treatment were done to the material, a stronger and tougher microstructure will be gained.

Oil is used when a slower cooling rate is desired. Since oil has a very high boiling point, the transition from start of Martensite formation to the finish is slow and this reduces the likelihood of cracking. Oil quenching results in fumes, spills, and sometimes a fire hazard.

Quenching can also be done by plunging the hot steel in water. The water adjacent to the hot steel vaporizes, and there is no direct contact of the water with the steel. This slows down cooling until the bubbles break and allow water contact with the hot steel. As the water contacts and boils, a great amount of heat is removed from the steel. With good agitation, bubbles can be prevented from sticking to the steel, and thereby prevent soft spots. Figure 2.3 shows the microstructure of quenched low carbon steel. From the figure, martensite that is needle-like is introduced after quenching process.

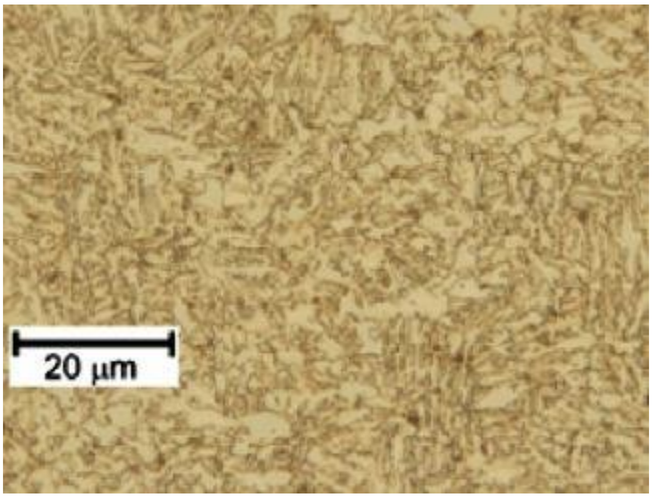

Figure 2.3: Microstructure of quenched low carbon steel

Source: Hilditch et al. (2011)

2.3.2 Tempering

Tempering is a process done subsequent to quench hardening. Quench-hardened parts are often too brittle. This brittleness is caused by a predominance of Martensite. This brittleness is removed by tempering. Tempering results in a desired combination of hardness, ductility, toughness, strength, and structural stability. Tempering is not to be confused with tempers on rolled stock-these tempers are an indication of the degree of cold work performed. The mechanism of tempering depends on the steel and the tempering temperature. The prevalent Martensite is a somewhat unstable structure. When heated, the Carbon atoms diffuse from Martensite to form a carbide precipitate and the concurrent formation of Ferrite and Cementite, which is the stable form. Tempering is done immediately after quench hardening. When the steel cools to about 40 ºC (104 ºF) after quenching, it is ready to be tempered. The part is reheated to a temperature of 150 to 400 ºC (302 to 752 ºF). In this region a softer and tougher structure Troostite is formed. Alternatively, the steel can be heated to a temperature of 400 to 700 ºC (752 to 1292 ºF) that results in a softer structure known as Sorbite. This has less strength than Troostite but more ductility and toughness. Figure 2.4 shows the microstructure of tempered low carbon steel.

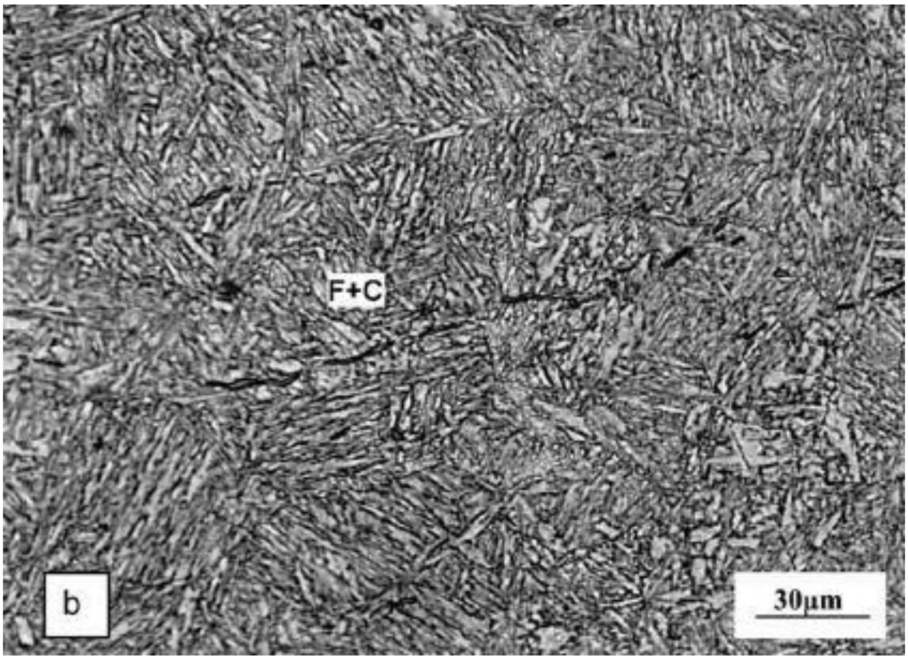

Figure 2.4: The microstructure of tempered low carbon steel

Source: Sankaran et al. (2003)